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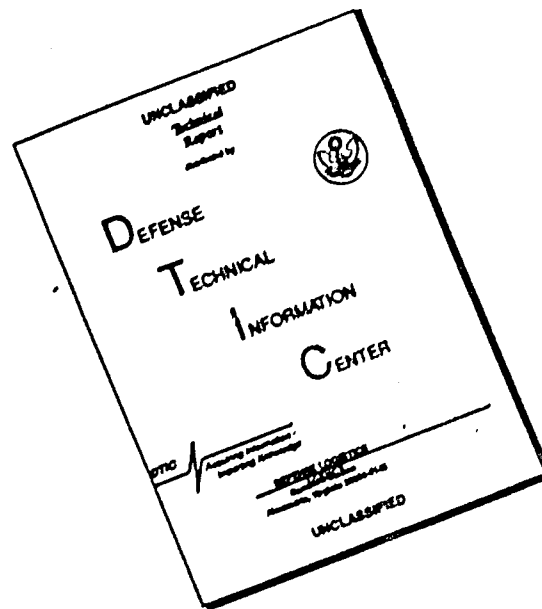
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MEMORANDUM

RM-3231-PR

AUGUST 1962

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THE SYNERGETIC PLANE CHANGE FOR ORBITING SPACECRAFT

F. S. Nyland



PREPARED FOR:

UNITED STATES AIR FORCE PROJECT RAND

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SANTA MONICA • CALIFORNIA

MEMORANDUM

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AUGUST 1962

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PREFACE

This Memorandum presents a preliminary analysis of a method for changing the orbital plane of a spacecraft operating in the vicinity of the earth. The method utilizes aerodynamic forces as well as propulsive forces to effect such maneuvers and has been named a synergetic plane change. The study was developed in conjunction with the continuing work on space-operation problems. The conclusions of this Memorandum should be of interest to strategy planners in the Air Force, specialists in the fields of atmospheric reentry and trajectory analysis, advanced vehicle designers, and those government agencies concerned with space.

SUMMARY

This Memorandum is the result of a preliminary investigation of a synergetic maneuver, which uses a combination of rocket propulsion and aerodynamic forces to obtain plane changes for orbiting spacecraft. Each phase of the maneuver--deorbiting, pullout, glide, ascent, and injection--is analyzed by the use of approximate closed form solutions to the equations of motion, when these equations cannot be solved analytically. The synergetic maneuver and a method using only propulsive devices are then compared.

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LIST OF SYMBOLS

A	aerodynamic reference area
C_D	aerodynamic drag coefficient
C_L	aerodynamic lift coefficient
D	drag force
d	air density (lb/ft^3)
d_o	sea level air density (0.07648 lb/ft^3)
$F(x)$	range function
g	acceleration due to gravity
h	altitude
I	amount of plane change
L	lift force
La	latitude
Lo	longitude
m	vehicle mass
R	position coordinate of vehicle along minor circle turn (range)
R_o	radius of the earth (3442 n mi)
r	distance from vehicle to earth's center
r_i	initial distance from vehicle to earth's center
r_t	turning radius
s	distance along a minor circle descent pattern
u	vehicle velocity
u_c	$u_o \sqrt{R_o/r}$ = circular orbit velocity
u_i	initial vehicle velocity
u_o	earth skimming satellite velocity (25,940 ft/sec)

u_r	reentry velocity
ΔV	velocity increment
W	vehicle weight (mass x gravity)
x	u/u_o
x_i	u_i/u_o
a	exponential coefficient of density distribution ($d = d_o e^{-\theta h}$)
γ	flight path angle
γ_a	initial path angle for ascent
γ_o	initial flight path angle
γ_r	reentry path angle
θ	earth-centered range angle
λ	arc length radius of minor circle
ϕ	vehicle bank angle
ψ	position coordinate of vehicle in minor circle turn (angular)

I. INTRODUCTION AND DEVELOPMENT

Large maneuvers by orbiting vehicles have, in the past, been studied primarily by considering changes in orbital parameters effected by rocket propulsion. It is widely known that changes in orbital altitude are comparatively less expensive in terms of energy than changes in orbital plane. This consideration is quite important because any propulsive devices used to change orbital parameters must be carried aloft by the spacecraft and its booster. Because of the small amounts of energy required for descent and ascent between orbits below 600 n mi, it is of interest to consider the use of aerodynamic forces for large changes in orbital plane. This study investigates a synergetic* maneuver that combines rocket propulsion and aerodynamic forces to obtain plane changes. The synergetic maneuver is then compared to a maneuver using propulsive devices only.

Synergetic plane changing by an orbiting vehicle consists of distinct phases of deorbiting, pullout, gliding, ascent, and injection (into the new orbit). First, the vehicle in a circular orbit would descend ballistically to the outer fringes of the atmosphere by application of a velocity decrement (ΔV_i). The vehicle could follow any one of a variety of paths to some lower altitude, one of which would be a Hohmann transfer semiellipse.** A ballistic descent over

* Synergetic: working together, cooperating.

** Hohmann transfer semiellipse: a transfer orbit between concentric coplanar circular orbits, and cotangent to them.

a shorter ground range might be used, but this would result in steeper reentry angles into the earth's atmosphere and larger loads might be imposed on the vehicle structure during the pullout phase. The pullout maneuver is executed by maintaining a constant vehicle lift to drag ratio (constant for purposes of analysis only) as it enters the upper portion of the atmosphere, and its purpose is to change the reentry path angle to a value compatible with the initial path angle required at the start of an equilibrium glide as well as to match the initial altitude of the next phase. In this analysis, it is assumed that the pullout maneuver is completed when the flight path angle is exactly zero. During the glide phase, the vehicle is banked, causing the resulting flight path to be a minor circle turn. Although other types of trajectories could be used, the minor circle turn is amenable to hand analysis. By the end of the glide phase, the vehicle velocity has decreased. A velocity increment (ΔV_2) is applied to bring the vehicle velocity up to orbital speed at the end of this phase. In conjunction with this speedup, a further velocity increment (ΔV_3) is required to initiate the transfer to the new orbit. After following the transfer trajectory to apogee, another velocity increment (ΔV_4) is required to inject the spacecraft into the new orbit. The total velocity requirement is the sum of the velocity increments associated with each phase of the maneuver shown in Fig. 1. The total velocity required for the synergetic maneuver is expressed as follows:

$$\Delta V = \Delta V_1 + \Delta V_2 + \Delta V_3 + \Delta V_4 \quad (1)$$

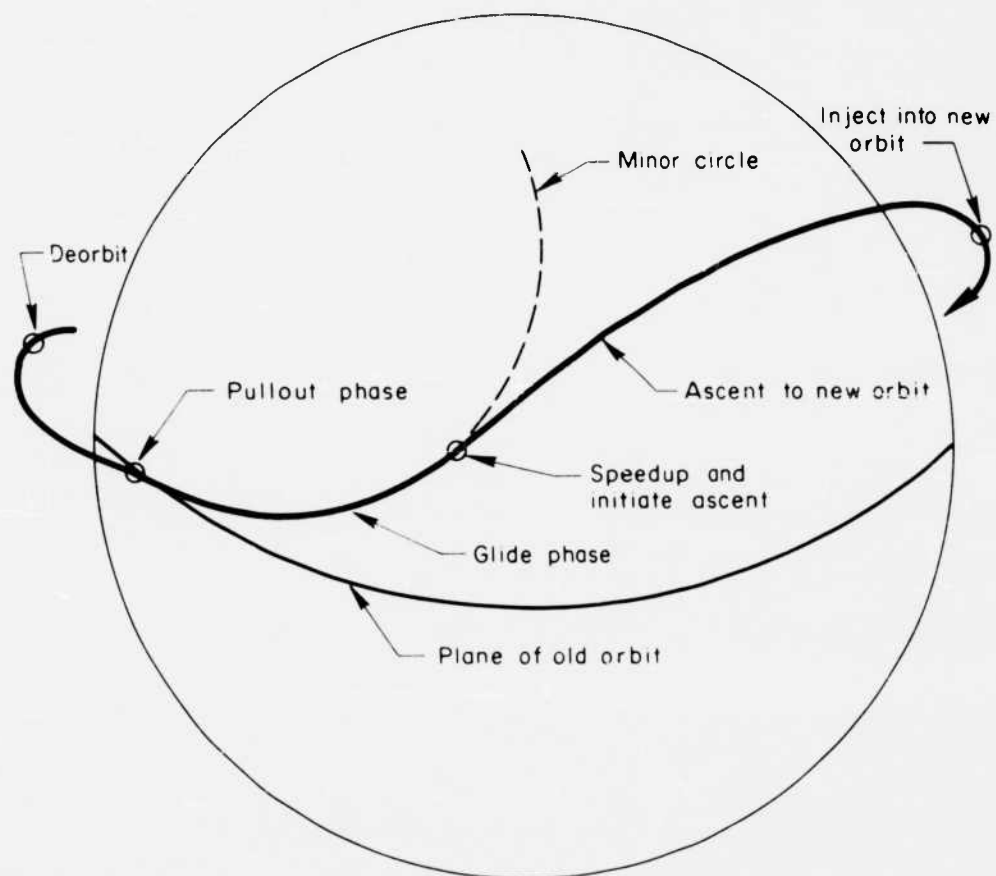


Fig. 1—Synergetic plane changing

where ΔV_1 = velocity increment required to descend from old orbit

ΔV_2 = velocity lost during the glide phase

ΔV_3 = velocity increment required to initiate ascent to new orbit

ΔV_4 = velocity increment required to inject into new orbit

Although the synergetic change in orbit plane is admittedly more complicated than the more direct method of using only rocket propulsion at the orbit altitude, it may be advantageous from the viewpoint of minimizing energy under certain conditions for lifting vehicles.

DESCENT FROM ORBIT

The descent path from the old orbit to the fringe of the atmosphere is a ballistic trajectory. There are many such paths, but for the descent of a glider one would wish to choose a path that would result in a small reentry angle. Thus a Hohmann semiellipse where the descent takes place over a 180 deg arc about the earth's center (range angle), or a ballistic descent with a range angle of 90 deg might be suitable bounds for examination. The Hohmann semiellipse is the minimum energy descent path. The use of the smaller range angles should decrease the descent flight time, decrease uncertainties in position at the reentry point, but increase the reentry angle. For descents from low altitudes, below the Van Allen radiation belts, reentry angles can be kept to values less than 10 deg if the range angle is 90 deg or more. Under these conditions the ground range for the descent would be greater than 5400 n mi. Thus, decelerations during pullout would be kept within tolerable limits, and perhaps one might wish to pay the penalty of the extra energy required in

order to shorten the descent time. At the higher altitudes, however, longer range angles would be required to keep the reentry angle small, and to keep the reentry velocity within some assumed cooling system technical capability. In this analysis the descent path is assumed to end at an altitude of 34.4 n mi. Since the path angle and velocity will not change very much with slight variations about this altitude, the results of the analysis can be extended to make estimates in somewhat different regimes. If the descent is a Hohmann transfer semiellipse, the conditions at the termination of the descent would be a zero path angle, and a velocity slightly in excess of circular. The equations describing such descents are discussed elsewhere,⁽¹⁾ and are presented here in terms of the path angle and velocity along the path of the trajectory.

$$\frac{R_o}{r} = \frac{1}{C^2} + \left(\frac{1}{x_o} - \frac{1}{C^2} \right) \cos \theta - \frac{\tan \gamma_o}{x_o} \sin \theta$$

$$\tan \gamma = \frac{r}{R_o} \left[\left(\frac{1}{x_o} - \frac{1}{C^2} \right) \sin \theta + \frac{\tan \gamma_o}{x_o} \cos \theta \right]$$

$$u/u_o = \frac{(r_1/R_o) (u_1/u_o) \cos \gamma_o}{(r/R_o) \cos \gamma}$$

$$\text{where } x_o = r_1/R_o, \text{ and } C = (r_1/R_o) (u_1/u_o) \cos \gamma_o$$

The symbols are defined as follows:

R_o = radius of the earth

r = distance between vehicle and earth's center

r_i = initial distance between vehicle and earth's center

u = vehicle velocity

u_i = initial vehicle velocity

u_o = earth skimming satellite velocity (25,940 ft/sec)

γ = flight path angle

γ_o = initial flight path angle

θ = earth-centered range angle between initiation point and end of trajectory

For the Hohmann transfer, the final path angle and initial path angle are zero, and only the equations for initial velocity (u_i) and reentry velocity (u_r) are needed for this analysis.

$$u_i/u_o = \sqrt{\frac{2(1.01)}{\frac{r_i}{R_o} \left(1.01 + \frac{r_i}{R_o}\right)}} \quad (2)$$

$$u_r/u_o = \frac{\sqrt{2}}{1.01} \sqrt{\frac{1.01 r_i/R_o}{1.01 + r_i/R_o}} \quad (3)$$

For the long range ballistic descent ($\theta = 90$ deg), the initial path angle has been assumed zero for ease of calculation. This specification does not result in a minimum energy trajectory, but the energy requirements are only slightly greater than minimum at low orbital altitudes. The equations for initial velocity, final or reentry velocity, and reentry path angle for the long range ballistic descent are:

$$u_i/u_o = \sqrt{1.01} R_o/r_i \quad (4)$$

$$u_r/u_o = 1/\sqrt{1.01} \cos \gamma_r \quad (5)$$

$$\tan \gamma_r = 1.01 R_o/r_i - 1 \quad (6)$$

Graphs of these equations for descent from various altitudes are shown in Figs. 2, 3, and 4. The trajectory was ended at an altitude of 34.4 n mi above the earth's surface.

PULLOUT PHASE

Toward the end of the descent from orbit, a pullout maneuver is initiated to match the end conditions of the ballistic descent to the initial conditions required for a glide trajectory through the upper atmosphere. The pullout maneuver is assumed to end when the path angle of the vehicle (γ) is exactly zero. It is also assumed that a constant lift to drag ratio is maintained throughout the pullout. If a vehicle enters the earth's atmosphere at a larger path angle than that associated with the initial conditions of an equilibrium glide, the vehicle motion may be generally described as bouncing or skipping along the top of the atmosphere. If, at the bottom of the first skip, the lift to drag ratio is changed, a transition between ballistic descent and equilibrium glide can be achieved. A description of the pullout maneuver is not amenable to closed form solution under the assumption of many analyses of glide trajectories, since in these studies, the path angle was assumed to be very small, and to have a very small rate of change. Recently, however, one author⁽²⁾ has pointed out other assumptions and conditions that will allow a closed form solution even

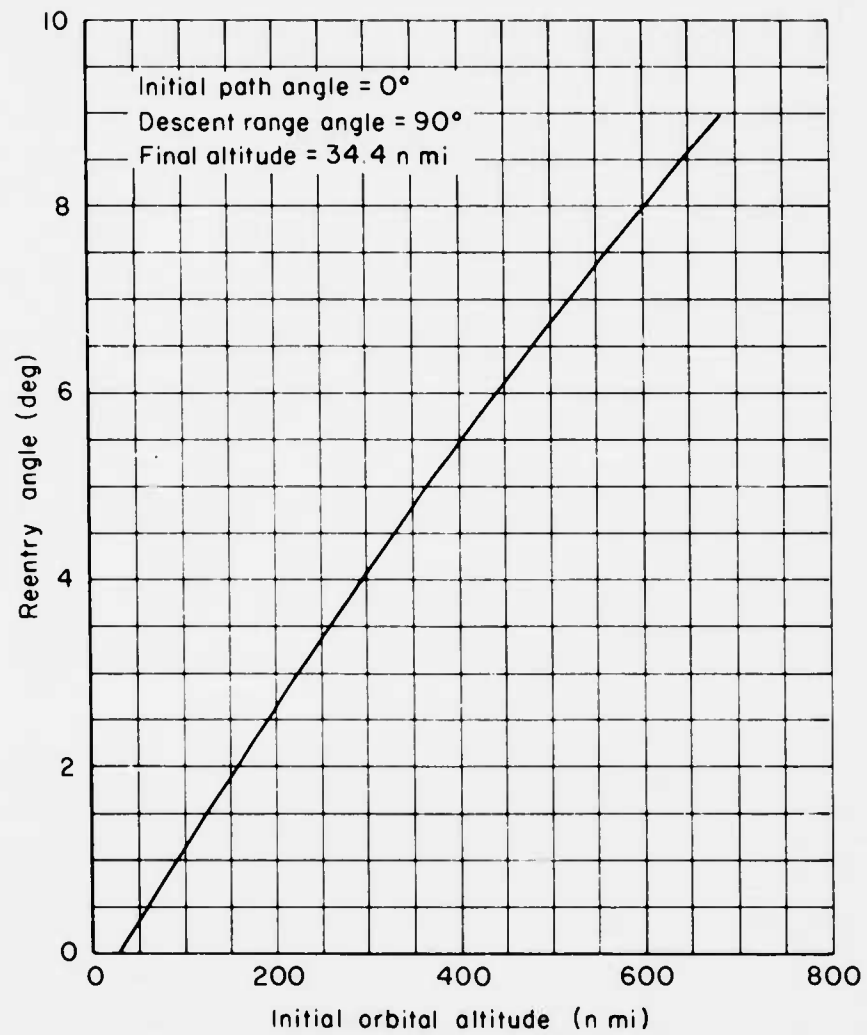


Fig. 2—Reentry angles for long-range ballistic descent

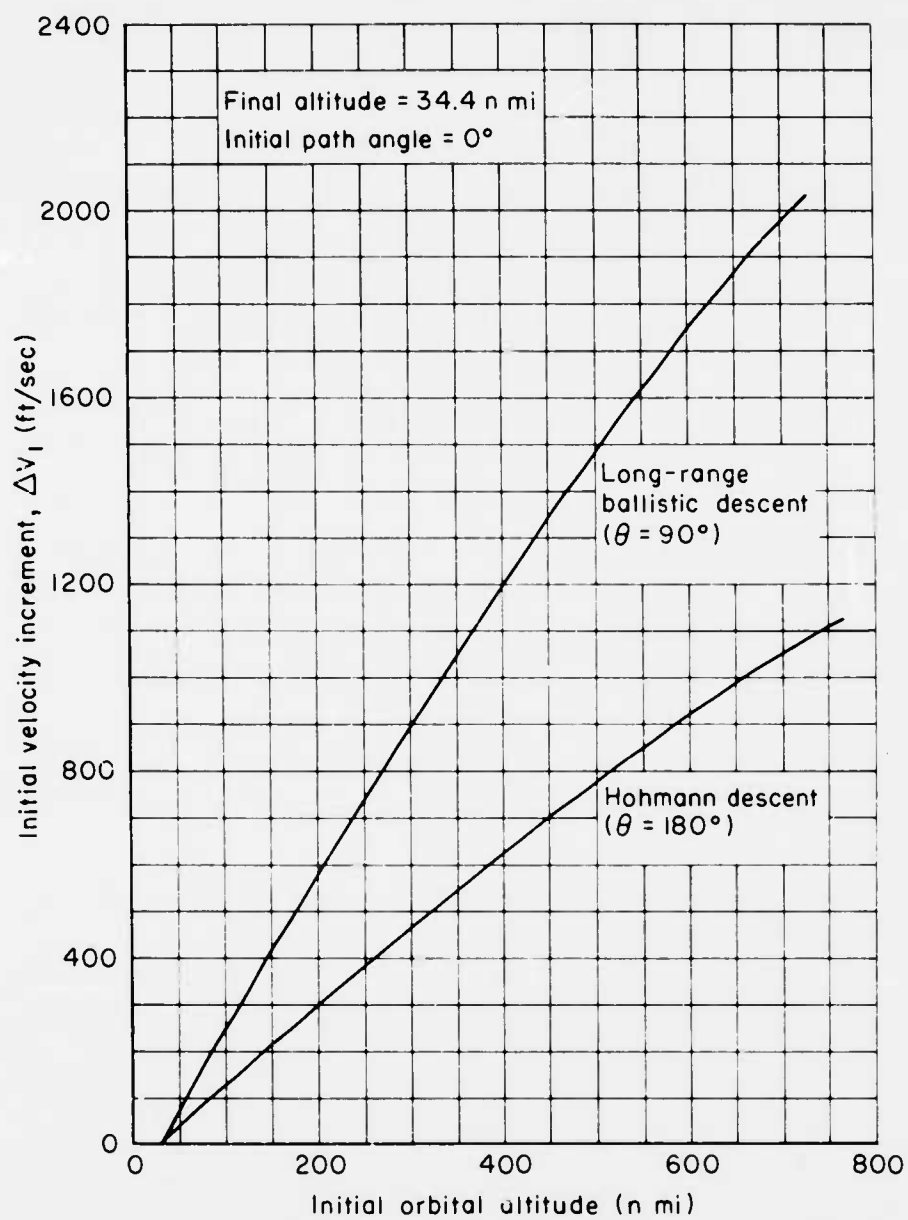


Fig. 3 — Velocity increment to descend from orbit

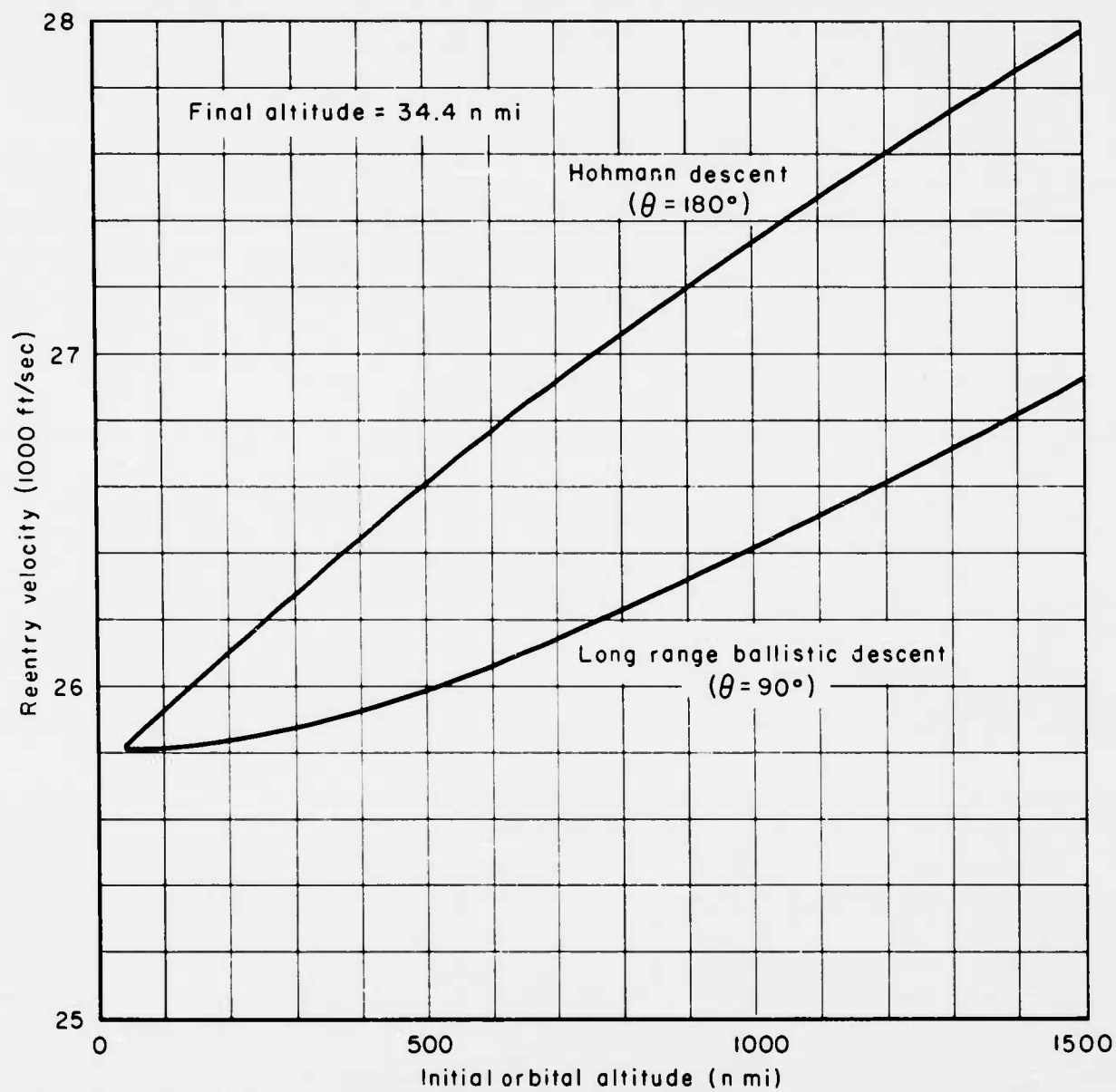


Fig. 4 — Reentry velocities for descent

when the flight path angle is a time-varying function. From this second order analysis, the flight path angle is a function of altitude and velocity of the reentering vehicle, and two different, but related, expressions have been derived.

$$\frac{1}{2} \frac{C_L A}{W} \frac{d\alpha}{\beta} e^{-\beta h} = 1 - \cos \gamma_r + \frac{1}{\beta R_0} \left(\frac{\alpha_0^2}{\alpha^2} - 1 \right) \quad (7)$$

$$\left(\frac{u_r}{u} \right)^{L/D} = e^{\gamma_r} \left[1 + \frac{(u_0^2/u^2 - 1)}{\beta R_0 (1 - \cos \gamma_r)} \right] \quad (8)$$

where the further symbol definitions are

A = aerodynamic reference area

C_L = aerodynamic lift coefficient

D = drag force

α_0 = sea level air density

h = altitude

L = lift force

W = vehicle weight

β = exponential coefficient of atmospheric density distribution
(1/24,000 ft)

Equation 7 permits solution for the altitude at the end of the pullout, at which time the velocity is known. A vehicle design parameter ($W/C_L A$) also enters into this calculation. Figure 5 shows the altitude at the end of pullout as a function of reentry angle for $W/C_L A = 1.0 \text{ lb/ft}^2$. Altitudes for other vehicle designs are readily calculated by subtracting a correction factor ($24,000 \log_e W/C_L A$) from the altitudes

given in Fig. 5. Equation 8 gives the ratio of reentry velocity and final velocities for the pullout. A further design parameter, the lift to drag ratio (L/D), is also a part of this calculation. Figures 6, 7, 8, and 9 show graphical solutions for selected values of velocity at the end of pullout ($0.9 u_0$, $1.0 u_0$, $1.1 u_0$, $1.2 u_0$). The amount of velocity lost during the pullout decreases with increasing L/D and with decreasing reentry angle. Thus, if velocity losses are to be minimized, high lift to drag ratios and/or small values of reentry angle should be used. The $W/C_L A$ of the given vehicle can be controlled by manipulating the vehicle angle of attack. The minimum value of this parameter, however, depends on basic design considerations: wing loading (W/A) and the maximum value of the aerodynamic coefficient.

For the Hohmann descent, no pullout maneuver is required. In the case selected, a final altitude at the end of the transfer of 34.4 n mi, the velocity at the end of the transfer calculated in the previous section neglects the effect of the earth's atmosphere. If the ballistic coefficient of the vehicle is high ($W/C_D A$), the velocity losses due to atmospheric drag in the final phase of the transfer will be very small. For the purposes of this analysis, such drag losses will be neglected since the descent to this point would be without use of lift forces. For example, the drag coefficient of Dyna-soar has been estimated to be about 0.03 when the angle of attack is zero. The $W/C_D A$ would then be about 1000 lb/ft^2 , and this value is normally considered fairly large. The special case for $L/D = 0$ has been treated⁽²⁾ and the pertinent

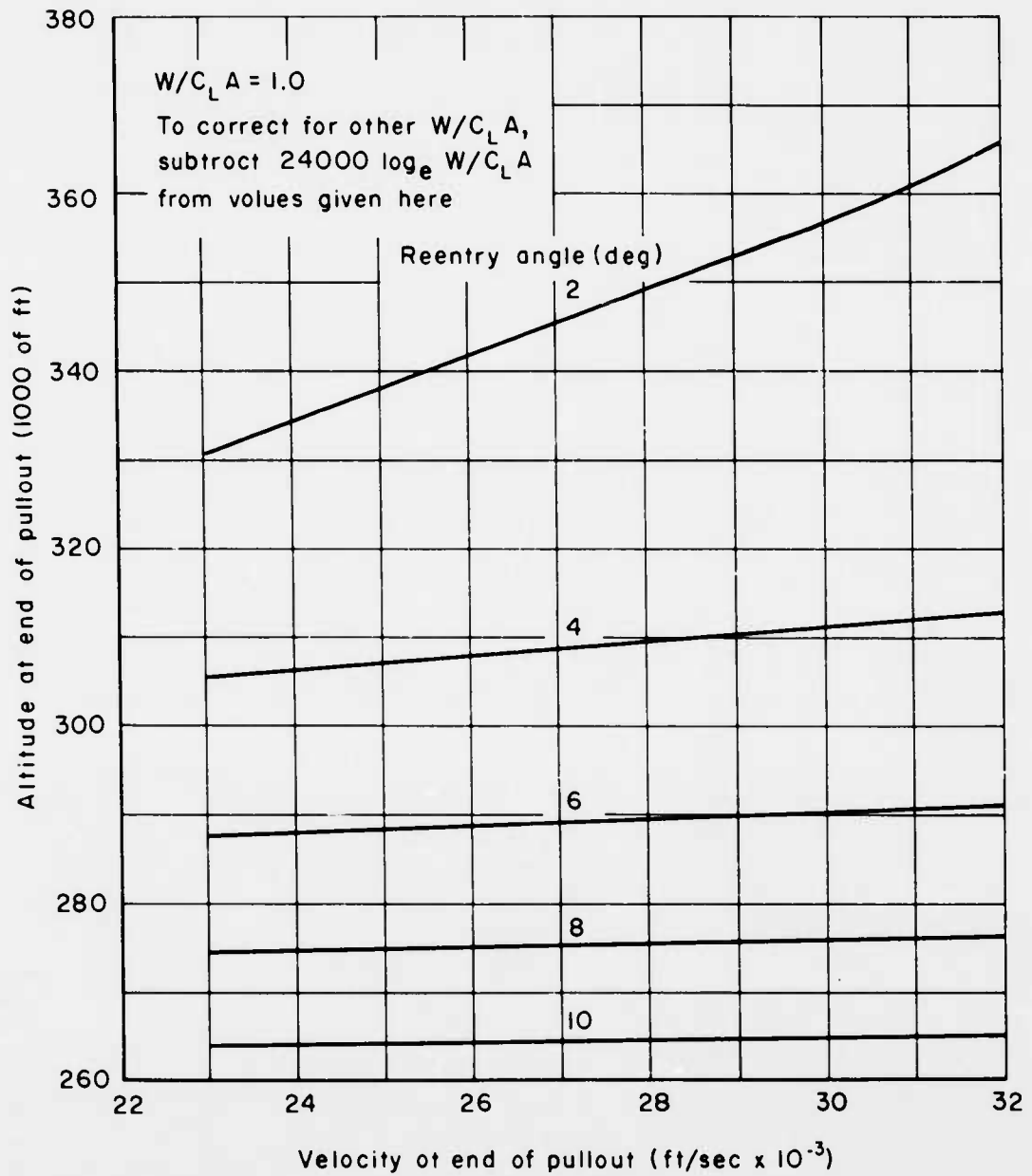


Fig. 5 — Pullout altitudes

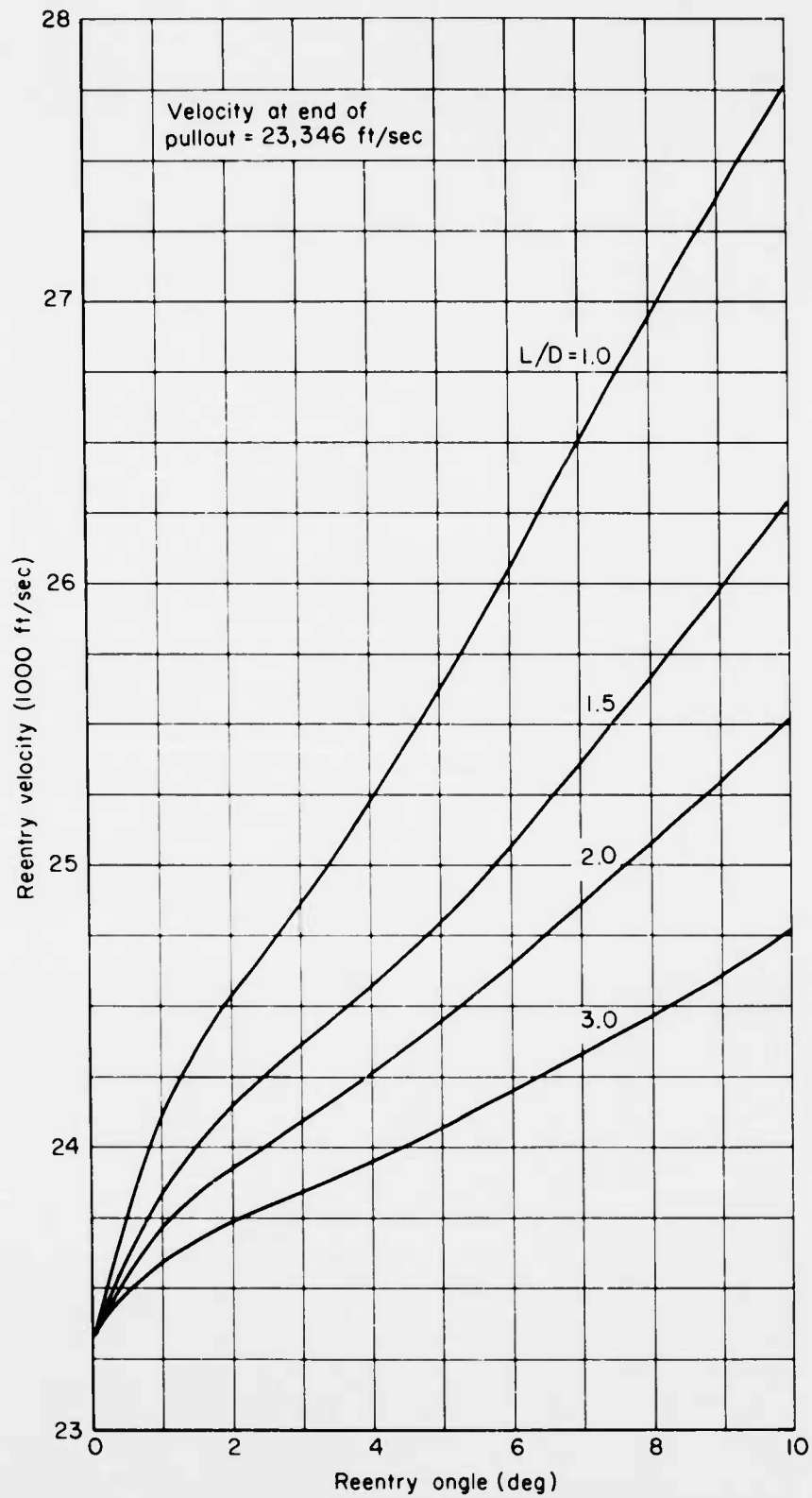


Fig. 6 — Pullout conditions ($u = 0.9 u_0$)

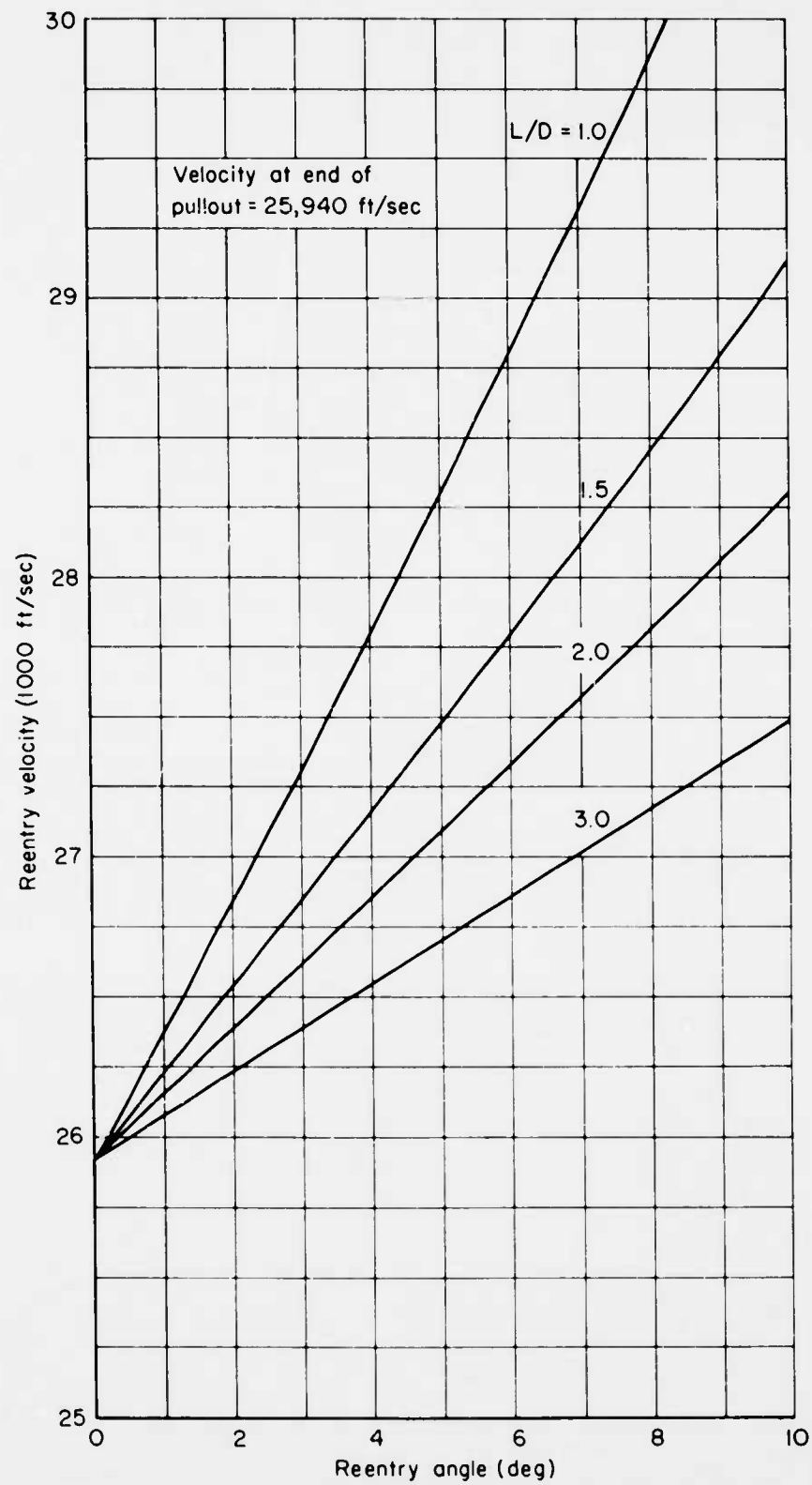


Fig. 7—Pullout conditions ($u = u_0$)

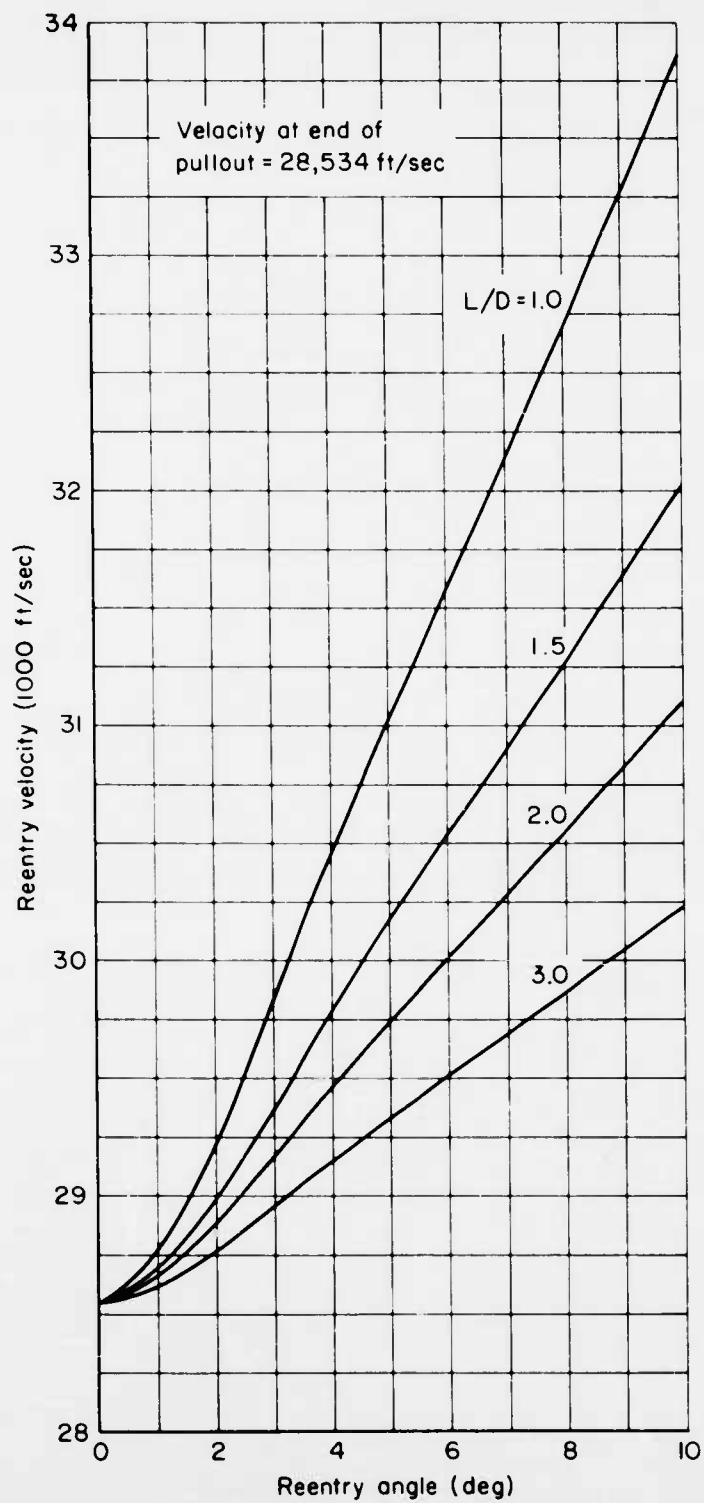


Fig. 8—Pullout conditions ($u = 1.1 u_0$)

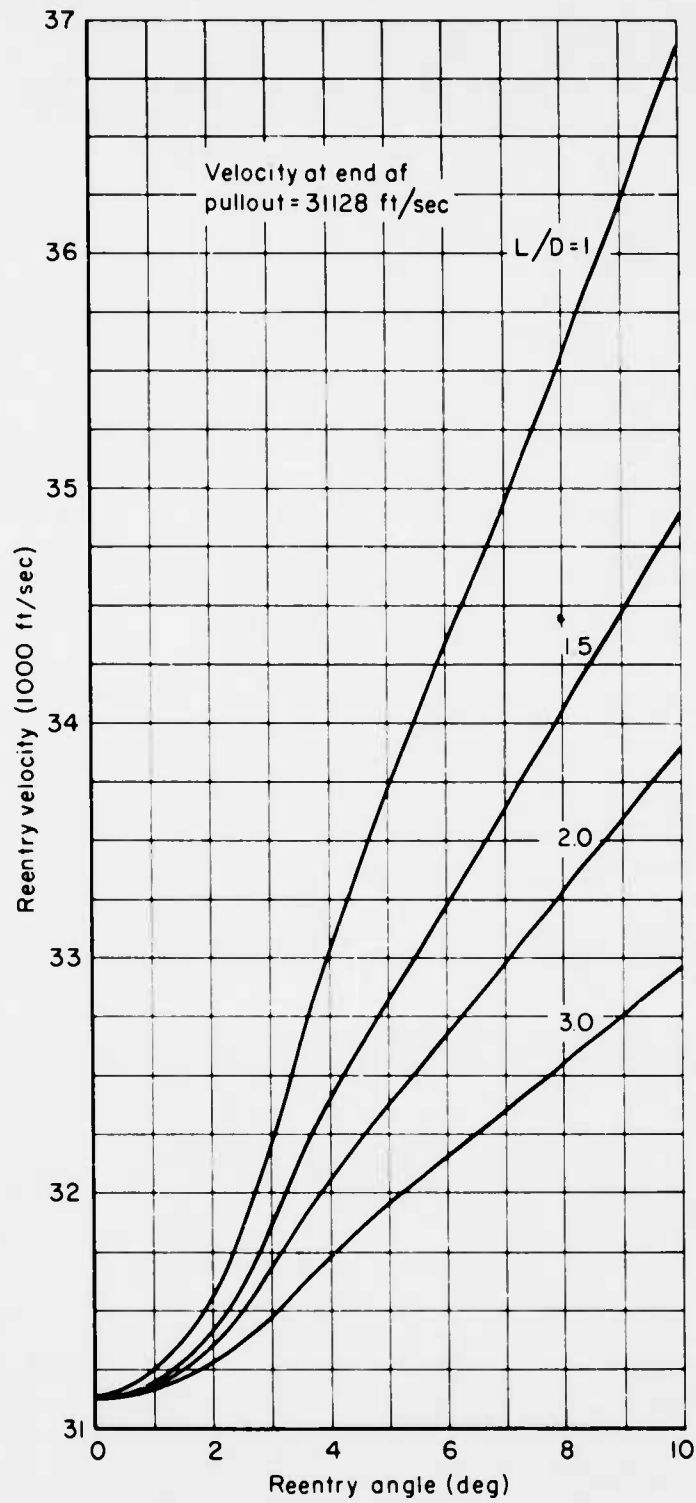


Fig.9 — Pullout conditions ($u = 1.2 u_0$)

relationship is

$$2 \log_e \frac{u_r}{u} = \frac{R_{OO} d (\gamma - \gamma_r) e^{-\beta h}}{(W/C_D A) \cos \gamma (u_O^2/u^2 - 1)}$$

From this equation it is seen that the difference between the reentry velocity (u_r) and the velocity at the end of the pullout (u) vanishes as the difference between flight path angles before and after pullout vanishes. If, however, accurate control over the flight path angle at the end of the Hohmann transfer cannot be maintained, then some velocity losses will result. Using the equation given above, it has been calculated that if the reentry angle is really 1 deg and the $W/C_D A$ of the vehicle is 1000 lb/ft², then the velocity loss will amount to 620 ft/sec. This velocity loss could not be neglected in a detailed analysis of the synergetic maneuver using a Hohmann descent from orbit.

GLIDE PHASE

During the glide phase, the vehicle is banked according to some function of velocity, time, or other variable. It is the turning during this phase that results in the large changes in orbital plane that are of primary interest in this study. Several types of turning trajectories have been studied by others, and these fall mainly into two classes. One method of turning is to hold the bank angle of a glide vehicle constant.⁽³⁾ Another method is to vary the bank angle of the vehicle in such a way that the trajectory is a circle⁽⁴⁾ (minor circle trajectory). For this study, the latter trajectory has been chosen because it is more amenable to hand analysis.

The geometry of a minor circle turn is shown in Fig. 10. Since it is often easier to visualize the descent from an equatorial orbit, such an example has been chosen here. This selection, however, does not restrict the generality of the equations that will be developed. It should be pointed out, however, that if a change in orbital plane is equal to a change in inclination, the line of intersection of the two planes must also be in the equatorial plane. The position of the vehicle along the minor circle turn is defined by the coordinate Ψ , which is the angle between the vehicle position and the initiation point of the turn measured about the center of the minor circle. The parameter defining the particular minor circle is λ , which is the radius of the minor circle measured as an arc length about the center of the earth. For example, the minor circle defined by $\lambda = 45$ deg would pass through the north pole if it is tangent to the equator. For the case of descent from an equatorial orbit, the latitude and longitude of the vehicle in terms of its position coordinate (Ψ) are found by solving the spherical triangle with its vertices at points A, E, and C.

$$\sin La = \frac{1}{2} (1 - \cos \Psi) \sin 2\lambda, La = DC \quad (9)$$

$$\sin Lo = \frac{\sin \lambda \sin \Psi}{\cos La}, Lo = AD \quad (10)$$

The position coordinate can further be defined as the ratio of the distance of the vehicle from the turn initiation point (AC) to the radius of the minor circle in its plane (turning radius).

$$\Psi = R/R_o \sin \lambda$$

where R is the range along the minor circle, and R_o is the earth's

radius. Since spherical triangles OAB and OCB are congruent,

AB = CB and then

$$\tan y = \tan (\psi/2) \sin \lambda$$

Solving triangle BDC

$$\sin I = \frac{\sin La}{\sin y}$$

After suitable manipulation

$$\sin I = \sin \psi \cos \lambda \sqrt{1 + \frac{1 - \cos \psi}{1 + \cos \psi} \sin^2 \lambda} \quad (11)$$

This equation specifies the new orbital plane with respect to the old orbit for any value of the position coordinate and is shown in Fig. 11.

The position coordinate is a function of the range along the minor circle, which in turn is related to the vehicle velocity loss as it decelerates in its glide path. Using the results of a previous analysis,⁽⁴⁾

$$R = \frac{R_0}{2} \frac{L}{D} \sin \lambda \left[\log_e |F(x_1)| - \log_e |F(x)| \right] \quad (12)$$

or relating this expression to the position coordinate

$$\psi = \frac{L}{2D} \left[\log_e |F(x_1)| - \log_e |F(x)| \right] \quad (13)$$

where $F(x)$, the range function, is given by

$$F(x) = 1 - \frac{x^2}{\sin^2 \lambda} - \frac{1}{\sin \lambda} \sqrt{\frac{x^4}{\sin^2 \lambda} - 2x^2 + 1} \quad (14)$$

and x is the ratio of vehicle velocity (u) to earth skimming orbit velocity (u_0). The logarithm of the range function is shown for various minor circles graphically in Fig. 12 and numerically in Appendix B. These can be used as calculating tools for making estimates.

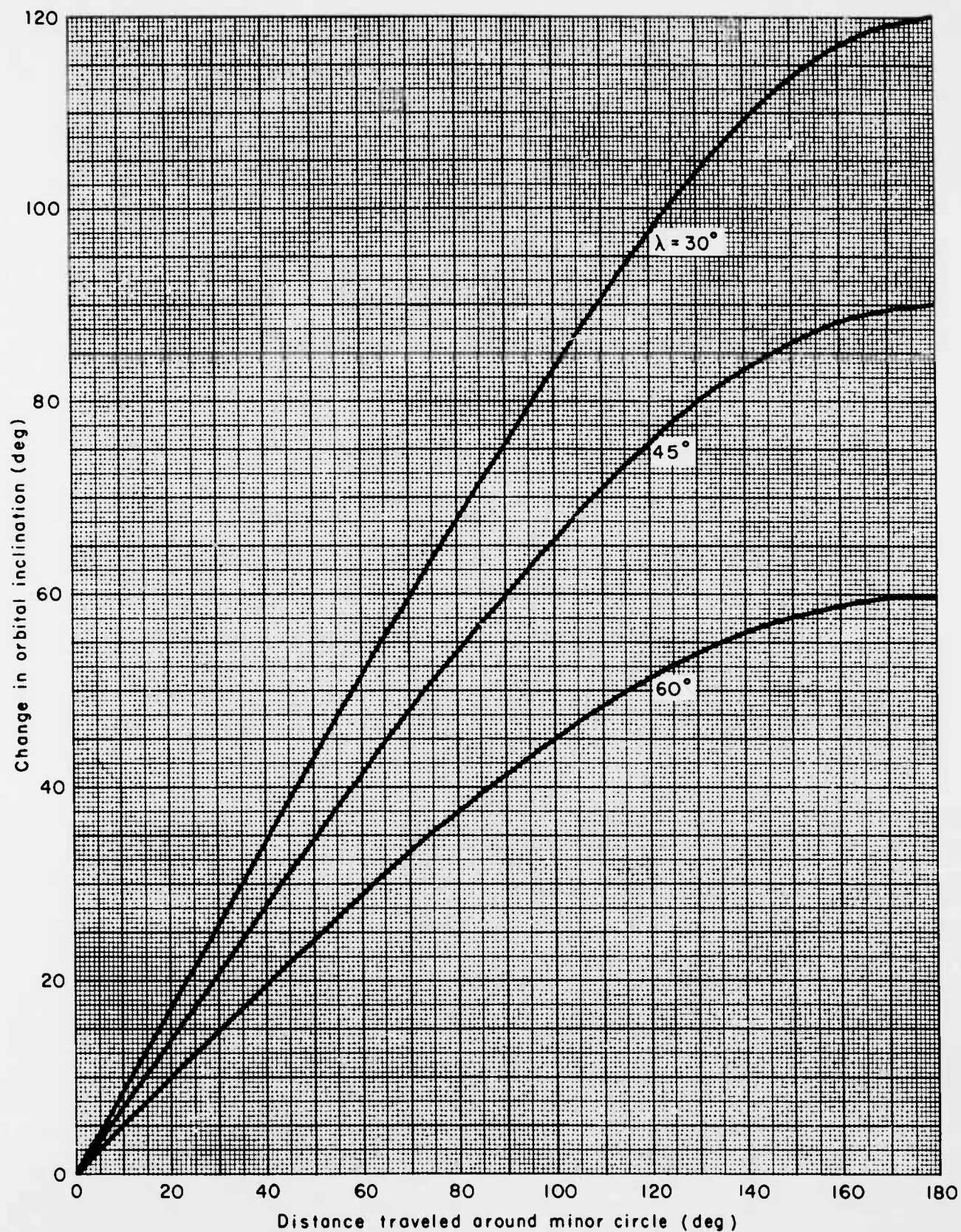


Fig. II—Orbital plane change and minor circle distances

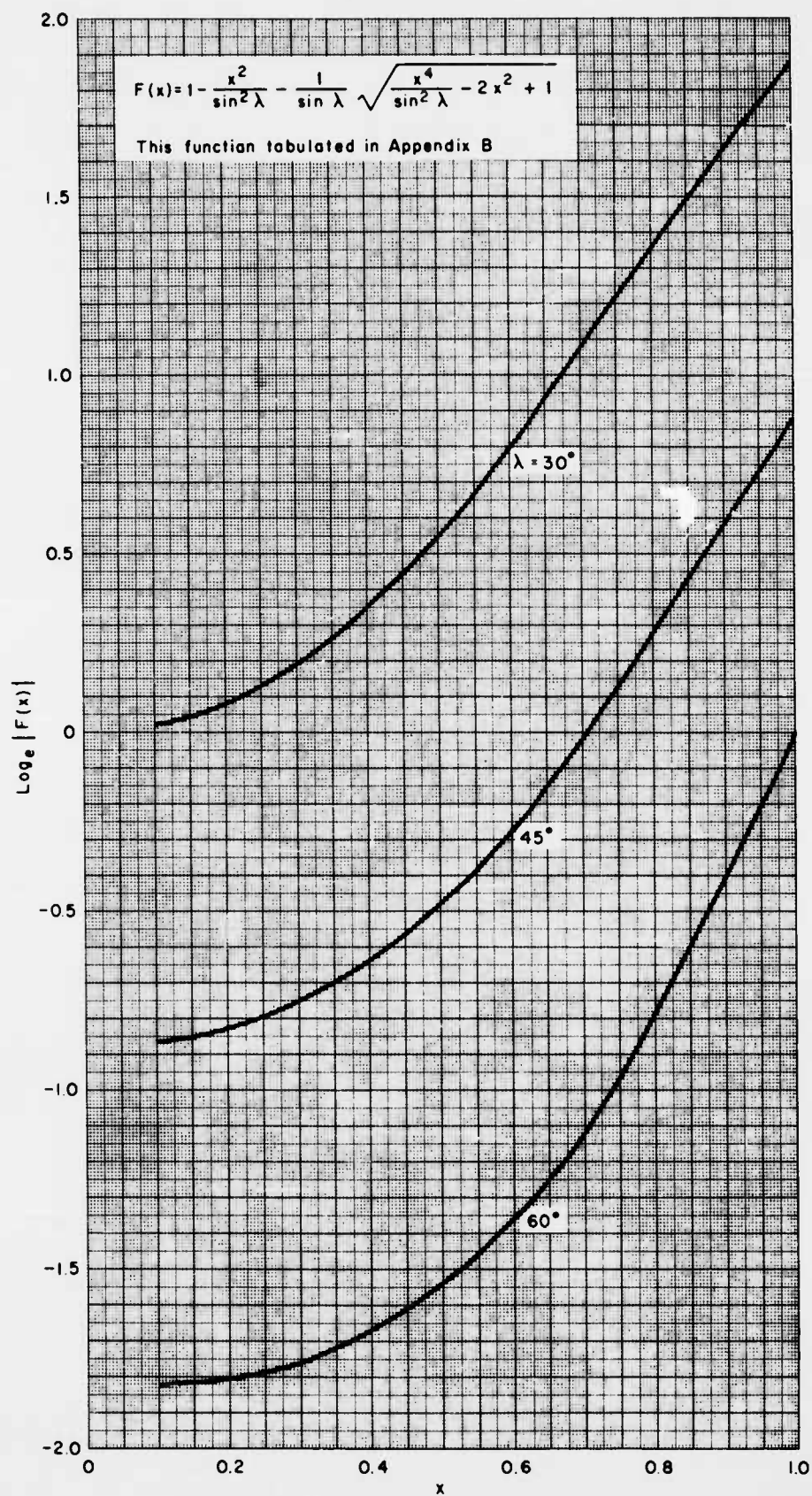


Fig. 12 — Range function

With the equations presented, it is possible to calculate the velocity lost by the vehicle during the glide phase in making a change in orbit plane. Examination of the equations indicates that if this velocity loss is to be minimized, a high lift to drag ratio is indicated. Although large changes in orbital plane can be accomplished by following trajectories with short turning radii, e.g., $\lambda = 30$ deg, such maneuvering will probably be prohibited by limitations of the cooling system in the vehicle. Thus, it may be more practical to consider more gently turning trajectories ($\lambda = 45$ deg or 60 deg) to avoid severe heating conditions associated with sharp turns.

ASCENT PHASE

At the end of the glide phase, the velocity of the vehicle must be restored to orbital. Beyond this velocity increment (ΔV_2), a further increment (ΔV_3) is required to initiate the ascent to the new orbit. If the ascent is a Hohmann semiellipse, then no change in path angle is required, and the incremental velocity change is applied parallel to the local horizon. If, however, the ascent trajectory is not a Hohmann transfer, then an angular change in flight path is required as well as increased magnitude in velocity. Because of the symmetry, one may use the result of calculations made in the section on the descent from orbit, or substitute the proper initial conditions in the general equations of motion.

For the Hohmann ascent, the velocity increment required to initiate the transfer from an orbit at 34.4 -n mi altitude is given by

$$\frac{\Delta V_3}{u_o} = \frac{1}{\sqrt{1.01}} \left(\sqrt{\frac{2 r/R_o}{1.01 + r/R_o} - 1} \right) \quad (15)$$

where r is the radius of the new orbit, and the constant 1.01 is the ratio of the assumed radius of the glide trajectory to the radius of the earth.

For the ballistic ascent to the new orbit, the path angle must be changed, and this additional effect is included in the following equations.

$$\Delta V_3 = \sqrt{u_r^2 + u_c^2 - 2 u_r u_c \cos \gamma_a} \quad (16)$$

$$\tan \gamma_a = 1 - 1.01 R_0/r \quad (17)$$

where Eq. 17 specifies the initial flight path angle (γ_a) required to initiate ascent to the new orbital altitude, and the magnitude of velocity change is given by Eq. 17, based on knowledge of the reentry velocity (u_r) developed in an earlier section of this Memorandum. Figure 13 shows the magnitude of the velocity change required to initiate ascent as a function of the altitude of the target orbit.

INJECTION PHASE

At the end of the ascent transfer, a velocity increment (ΔV_4) is applied to the space vehicle to inject into the new orbit. This method has previously been used in several Air Force space programs and is the familiar "kick in the apogee" method of orbit injection. The velocity increment required for this phase is exactly the same as that used to initiate the descent developed earlier. Thus, if the altitude of the old orbit and new orbit are the same,

$$\Delta V_1 = \Delta V_4 \quad (18)$$

if the descent and ascent trajectories are also identical. The major

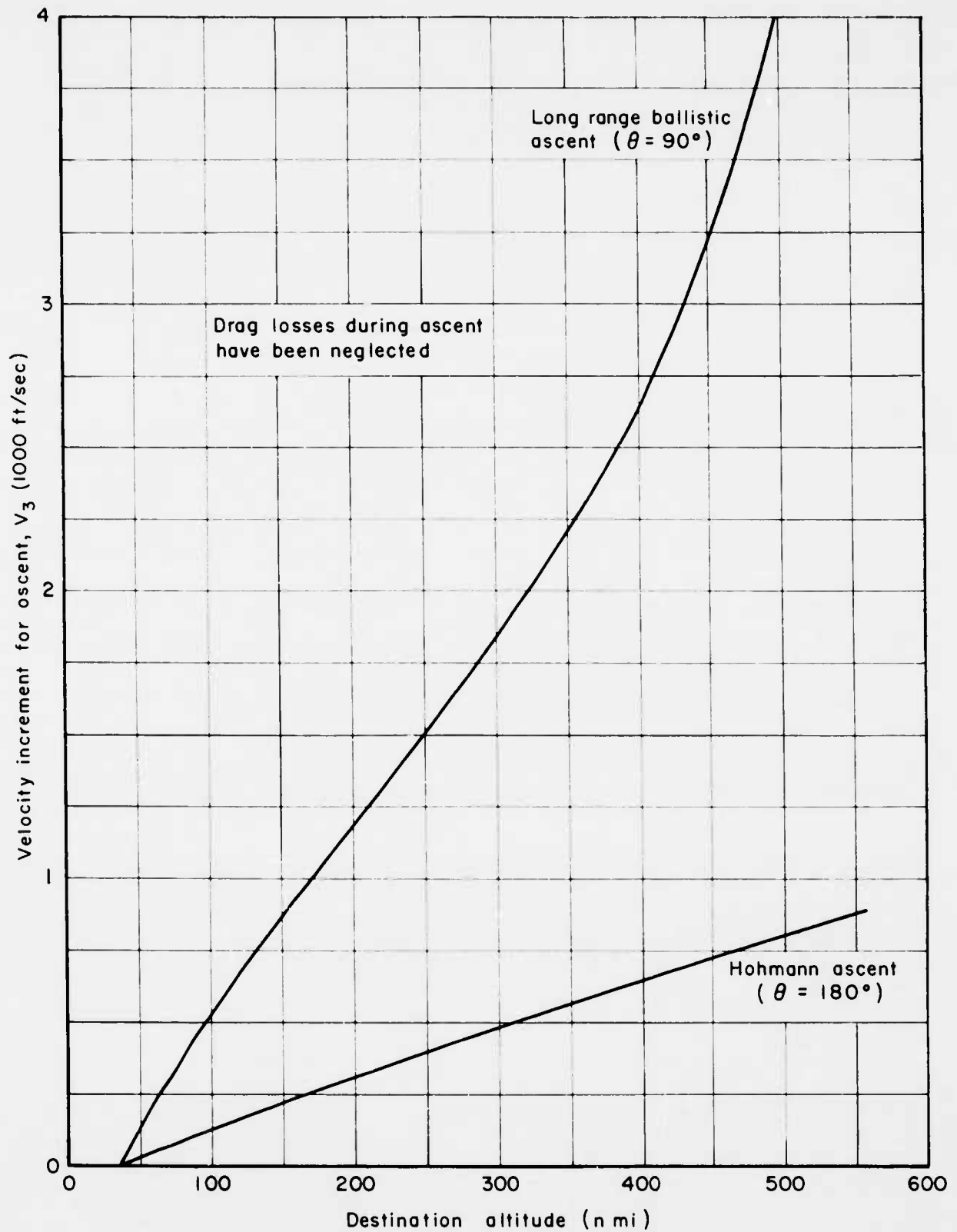


Fig. 13 — Velocity requirements for ascent phase

difference between the deorbit and injection phases is that the velocity increment associated with the deorbit phase tends to slow the spacecraft, whereas the velocity increment associated with injection tends to speed up the vehicle.

II. NUMERICAL EXAMPLE

This section presents a numerical example of the calculations outlined in this study, and demonstrates how the various phases of the synergetic plane changing maneuver are gathered together. During the course of this example, the influence of vehicle design parameters will be shown.

As a start, it will be assumed that a spacecraft complete with wings of some sort is orbiting the earth at an altitude of 300 n mi. It has been decided that an orbital plane change of 45 deg is required, and that the transfers for descent and ascent will be along the long range ballistic path ($\theta = 90$ deg) in an attempt to keep the time of the maneuver short. The orbital spacecraft has the following properties: $W/A = 30 \text{ lb/ft}^2$, $C_L \text{ max} = 0.6$, $C_L(\text{at max } L/D) = 0.15$, $L/D(\text{max}) = 3.0$. The initial velocity increment (ΔV_1) is applied to slow the spacecraft down. The magnitude is taken from Fig. 3 (p. 8), and $\Delta V_1 = 899 \text{ ft/sec}$. Subsequently, the vehicle descends along a ballistic trajectory to the reentry point in the earth's atmosphere. The reentry velocity is 25,876 ft/sec (Fig. 4, p. 9) and the reentry angle is 4 deg (Fig. 2, p. 7). Using a constant L/D during the pullout ($L/D = 3$), the velocity at the end of pullout is 25,257 ft/sec. Assuming that the equilibrium glide is to be flown at maximum L/D , the $W/C_L A$ during the glide phase is 200 lb/ft^2 . Calculating the initial altitude for this phase by use of Fig. 16 (p. 40), one finds that at an initial velocity of 25,257 ft/sec and a $W/C_L A$ of 200 lb/ft^2 , the

initial altitude would have to be 198,000 ft for a minor circle turn specified by $\lambda = 45$ deg. Thus, the altitude at the end of the pullout should also be 198,000 ft to match initial conditions for the glide phase. Using the information on Fig. 5 (or Eq. 7), one finds that if a $W/C_L A$ of 1 lb/ft^2 is used during the pullout maneuver, the final altitude would be 307,000 ft, 109,000 ft too high. The $W/C_L A$ during pullout is calculated by applying the correction factor noted earlier in the discussion of Fig. 5 (p. 12), and the $W/C_L A$ should be 94 lb/ft^2 (by the correction factor, $24,000 \log_e W/C_L A = 109,000$).

During the glide phase, the orbital inclination is required to change by 45 deg. Figure 11 shows that the distance traveled around the minor circle (ψ) should be 65.5 deg or about 1.14 radians. Substituting this value for the position coordinate and an L/D ratio of 3 into Eq. 13,

$$1.14 = \frac{3}{2} [\log_e |F(x_1)| - \log_e |F(x)|]$$

and knowing that $x_1 = 0.974 = 25,257/25,940$, one can determine the velocity of the vehicle when the required turn has been achieved. From Fig. 12 (p. 22), $\log_e |F(x_1)| = 0.805$. Subtracting 0.762 from this value yields 0.043 . By finding the value of $\log_e |F(x)| = 0.043$ on Fig. 12, $x = 0.722$, one then finds that the velocity at this time is $18,731 \text{ ft/sec}$ ($0.722 \times 25,940$). At the end of the glide phase, a velocity increment (ΔV_2) is applied to bring the vehicle velocity to orbital speed. Orbital speed is given by $u_c = u_o \sqrt{R_o/r}$, and for altitudes near 34.4 n mi , $u_c = 25,811$. Thus, $\Delta V_2 = 25,811 - 18,731 = 7080 \text{ ft/sec}$. Once the orbital speed is restored, a further velocity increment

(ΔV_3) is required to initiate transfer to 300 n mi. The path angle and velocity change are given by Eqs. 16 and 17. In this case $\Delta V_3 = 1833$ ft/sec and the initial path angle for the ascent is the same as the reentry angle, 4 deg. The velocity increment (ΔV_4) required for injection at the apogee of the transfer trajectory is the same as ΔV_1 and amounts to 899 ft/sec. Finally, the total velocity required to accomplish the entire maneuver is the total of the increments, and in this case amounts to 10,711 ft/sec. If the maneuver were accomplished by pure rocket power at orbital altitude, the velocity increment required would be 19,041 ft/sec.

III. CONCLUSIONS

This study has presented an analysis of synergetic plane changing for orbiting spacecraft designed for lifting reentry. Each phase of the maneuver has been analyzed through the use of approximate closed form solutions to the equations of motion, when these cannot normally be solved analytically. Certain drag losses have been neglected (for example, the drag loss associated with the speedup and ascent to orbit), but these are not large enough to affect the general nature of conclusions drawn from a preliminary analysis such as this one. In an example it was shown that a 45 deg plane change could be accomplished with a synergetic maneuver with less energy expenditure than by use of pure rocket propulsion in space. The difference in velocity requirements was not great, but the descent and ascent trajectories were not minimum energy trajectories. If minimum energy descent and ascent trajectories, namely Hohmann semi-ellipses, are chosen, considerable savings in energy are possible. The velocity required to effect an orbital plane change in space is given by

$$\Delta V = u_c \sqrt{2 (1 - \cos I)} = 2 u_c \sin \frac{I}{2} \quad (19)$$

where I is the amount of plane change, and u_c is the orbital velocity. Using the material developed in this study, it is possible to compare the energy expenditure required to change planes by the two methods. For this comparison, the descent and ascent phases of the synergetic maneuver will be Hohmann transfer semiellipses. Figure 14 shows the

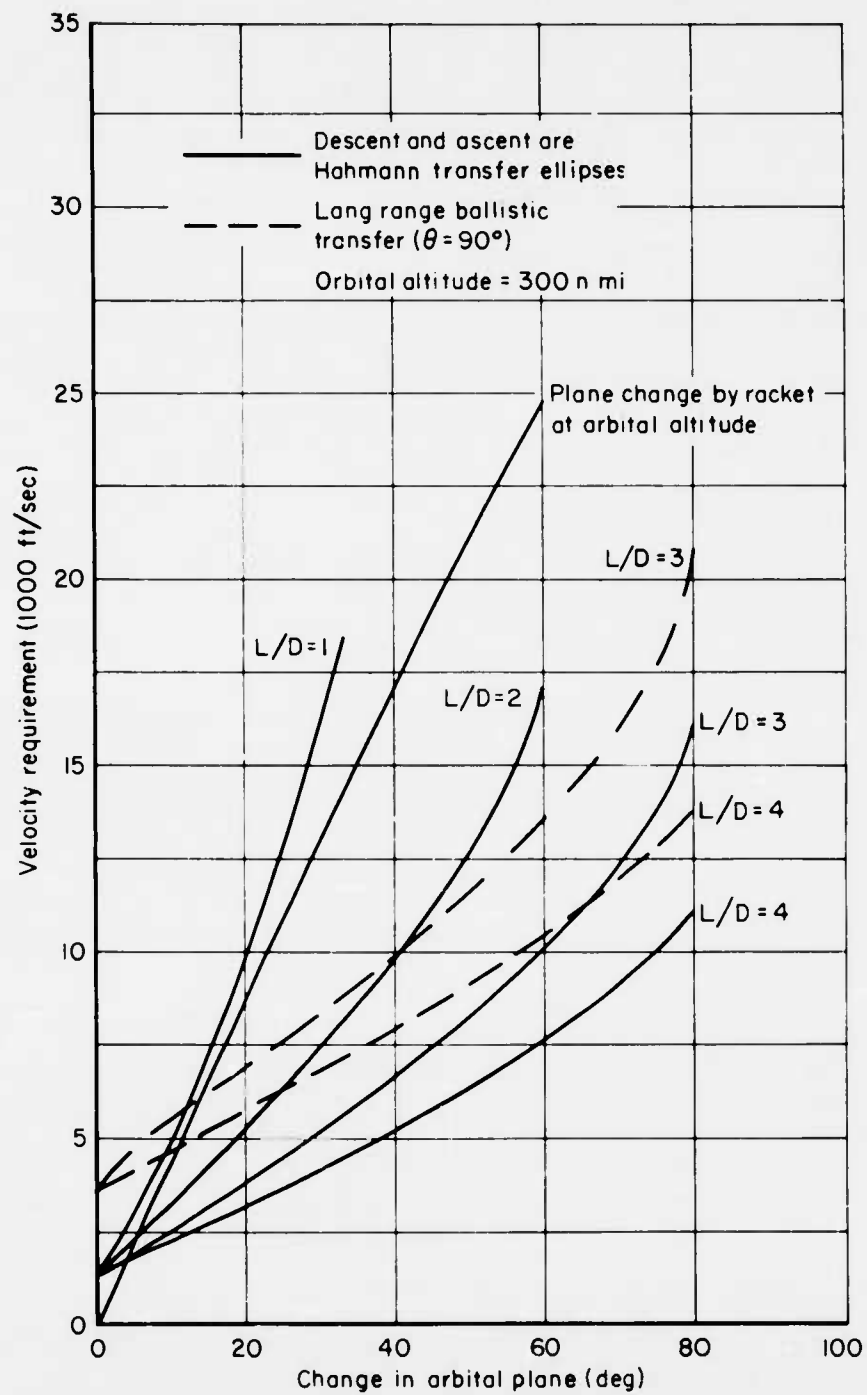


Fig.14—Total velocity requirements for two methods of plane changing

velocity requirements for various amounts of orbital plane change for both methods, assuming an orbital altitude of 300 n mi. Table 1 gives a more detailed accounting of the amounts of various velocity increments for the synergetic plane change. Variations in altitude about this reference case will not drastically affect the results, and will not change the basic trends. Since the lift to drag ratio of a lifting vehicle also affects the performance during the glide phase of the synergetic plane change, the effects of variations of this parameter are also shown. It is seen immediately that lift to drag ratios less than unity will not result in any saving in energy over the rocket method. In fact, it would be more costly to use synergetic plane changing for low lift to drag ratios. If plane changes are restricted to values less than 5 deg, it is also more costly to employ synergetic plane changing even when using Hohmann transfers. If large orbital changes are required for a given mission ($I \gtrsim 5$ deg), it appears that synergetic plane changing can be much less costly than the direct method of rocket propulsion alone, if the lift to drag ratio of the spacecraft is reasonably large. The larger the lift to drag ratio, the larger the saving in using the synergetic method. For very large orbital plane changes, however, the synergetic method will become more expensive than the rocket method. The reason for this trend is that so much energy is lost by the vehicle during the turning glide phase, it is almost as economical to land the vehicle, put it back on a booster at a launch pad, and then launch it back into orbit. Thus, even the synergetic method of changing planes has its limits.

The use of multiple thrusting periods during the glide phase of the vehicle may offer an alternative method for improving the

Table 1

VELOCITY INCREMENTS REQUIRED FOR SYNERGETIC PLANE CHANGING*

Plane change = 15°

	ΔV_1	ΔV_2	ΔV_3	ΔV_4	ΔV
$\frac{L}{D} = 1$	462	5,888	470	462	7,282
$\frac{L}{D} = 2$	462	2,801	470	462	4,195
$\frac{L}{D} = 3$	462	1,764	470	462	3,158
$\frac{L}{D} = 4$	462	1,219	470	462	2,613

Plane change = 30°

	ΔV_1	ΔV_2	ΔV_3	ΔV_4	ΔV
$\frac{L}{D} = 1$	462	14,345	470	462	15,739
$\frac{L}{D} = 2$	462	5,914	470	462	7,308
$\frac{L}{D} = 3$	462	3,865	470	462	5,259
$\frac{L}{D} = 4$	462	2,827	470	462	4,221

Plane change = 60°

	ΔV_1	ΔV_2	ΔV_3	ΔV_4	ΔV
$\frac{L}{D} = 1$	462	--- ^a	470	462	--- ^a
$\frac{L}{D} = 2$	462	15,693	470	462	17,087
$\frac{L}{D} = 3$	462	8,664	470	462	10,058
$\frac{L}{D} = 4$	462	6,225	470	462	7,619

* Initial and final orbital altitudes are 300 n mi. Transfers are by Hohmann semiellipses to and from an altitude of 34.4 n mi.

^a Land vehicle and launch to orbit in new plane.

efficiency of the synergetic plane change for large changes in plane. Examination of Table 1 shows that with an L/D of 2 and a plane change of 60 deg, it would be more economical to use two plane changes of 30 deg. Even this multiple maneuver may be improved somewhat by merely restoring speed in the glide phase after the first 30 deg of plane change has been accomplished so that the second part of the turn is initiated at a higher speed. This improvement would not require that the vehicle be boosted back up to an orbit outside the atmosphere. Thus the logic of this type of improved synergetic plane change could be represented by the equation,

$$\Delta V = 2\Delta V_1 + 2\Delta V_2 + \Delta V_3$$

where, for a 60-deg plane change, the two ΔV_2 s are those associated with a plane change of 30 deg. With this improvement, a 60-deg plane change would require a total velocity increment of 13,222 ft/sec as opposed to making a single maneuver that would require 17,087 ft/sec. Thus it would appear that further study is required to examine the use of multiple thrusting, or the possibility of using continuous thrust during the glide phase to maintain constant speed in the atmosphere.

If the orbital altitude of the spacecraft is increased by an order of magnitude or more, the synergetic method is more costly than ever. At the same time, the velocity increment required to change planes directly at altitude has decreased by an amount indicated in Eq. 19. The relative tradeoffs in methods are shown for a 15-deg plane change as a function of altitude in Fig. 15. The

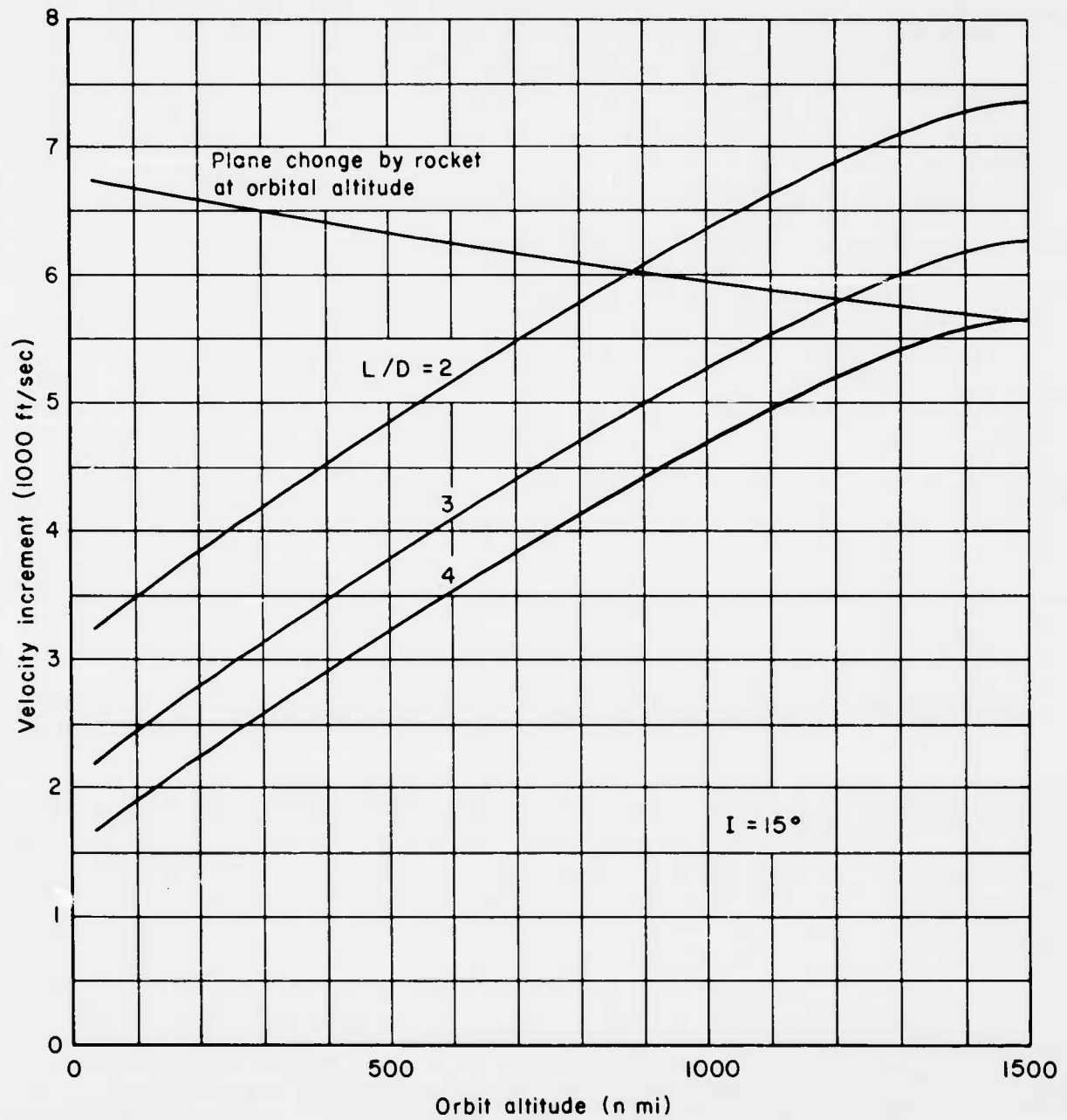


Fig. 15 — Velocity increments required for plane changes at other altitudes

synergetic method becomes more expensive at higher orbital altitudes because of the increased velocity requirements for the descent to and ascent from the earth's atmosphere. Additionally, the weight of the vehicle would have to increase, because a more efficient cooling system would be required to withstand the higher speed reentries into the atmosphere. Thus, the use of synergetic plane changing is restricted to lower altitudes where reentry parameters will fall within the boundaries established by cooling technology. At the lower altitudes, the maneuver is a method of conserving energy when large plane changes are required.

Appendix A

GRAPHIC GLIDE TRAJECTORY CALCULATOR

Those working in the field of reentry dynamics often need to calculate preliminary data concerning the flight trajectory and to investigate trajectory and vehicle design interactions. This appendix presents a simple graphical device that will provide trajectory information for glide reentry into the earth's atmosphere.

The equations of motion of glide vehicles reentering the earth's atmosphere have been discussed by many authors. Since the primary interest in this Memorandum is in turning glide trajectories, equations that include these effects have been selected.⁽⁴⁾ The basic equations of motion can be combined after certain reasonable assumptions to give:

$$\frac{du^2}{ds} + \frac{2g}{L/D} \sqrt{\cos^2 \lambda + \sin^2 \lambda \left(1 - \frac{u^2}{u_o^2 \sin^2 \lambda}\right)^2} = 0 \quad (20)$$

$$\sin(\lambda - \phi) = \frac{\sin \lambda (1 - u^2/u_o^2 \sin^2 \lambda)}{\sqrt{1 - 2 \frac{u^2}{u_o^2} + \frac{u^4}{u_o^4 \sin^2 \lambda}}} \quad (21)$$

where

g = acceleration due to gravity

L/D = vehicle lift to drag ratio

s = distance along a minor circle descent path

u = vehicle velocity

u_o = earth skimming satellite velocity (25,940 ft/sec)

λ = arc length radius of minor circle (about the earth's center)

ϕ = vehicle bank angle

The assumptions made in deriving these equations are that the initial path angle is nearly zero, and that the distance from the vehicle to the earth's center is approximately equal to the earth's radius. A nonrotating spherical earth is also assumed. If it is further assumed that the density of the atmosphere is exponentially distributed as a function of altitude, then an altitude-vehicle velocity relationship can be established.

$$\beta h = \log_e \frac{R_o d_o}{2} - \log_e \frac{W}{C_L A} - \log_e \sqrt{\left(\frac{u_o^2}{u^2} - 1\right)^2 + \cos^2 \lambda} \quad (22)$$

where

A = aerodynamic reference area

C_L = aerodynamic lift coefficient

d = air density

d_o = sea level density of air (lb/ft³)

R_o = earth radius

W = vehicle weight

β = exponential distribution constant ($d = d_o e^{-\beta h}$)

This equation is particularly useful in preliminary design determinations.

The shape of this function of velocity is independent of vehicle design, and depends only on specific values of the radius of the minor circle path. Changes of vehicle configuration, namely $W/C_L A$, result in a logarithmic translation of this basic curve, or set of basic curves corresponding to various minor circle radii. Thus it is possible to make one calculation and extend it for all values of aerodynamic wing loading. Figure 16 shows the result of this calculation for a wing

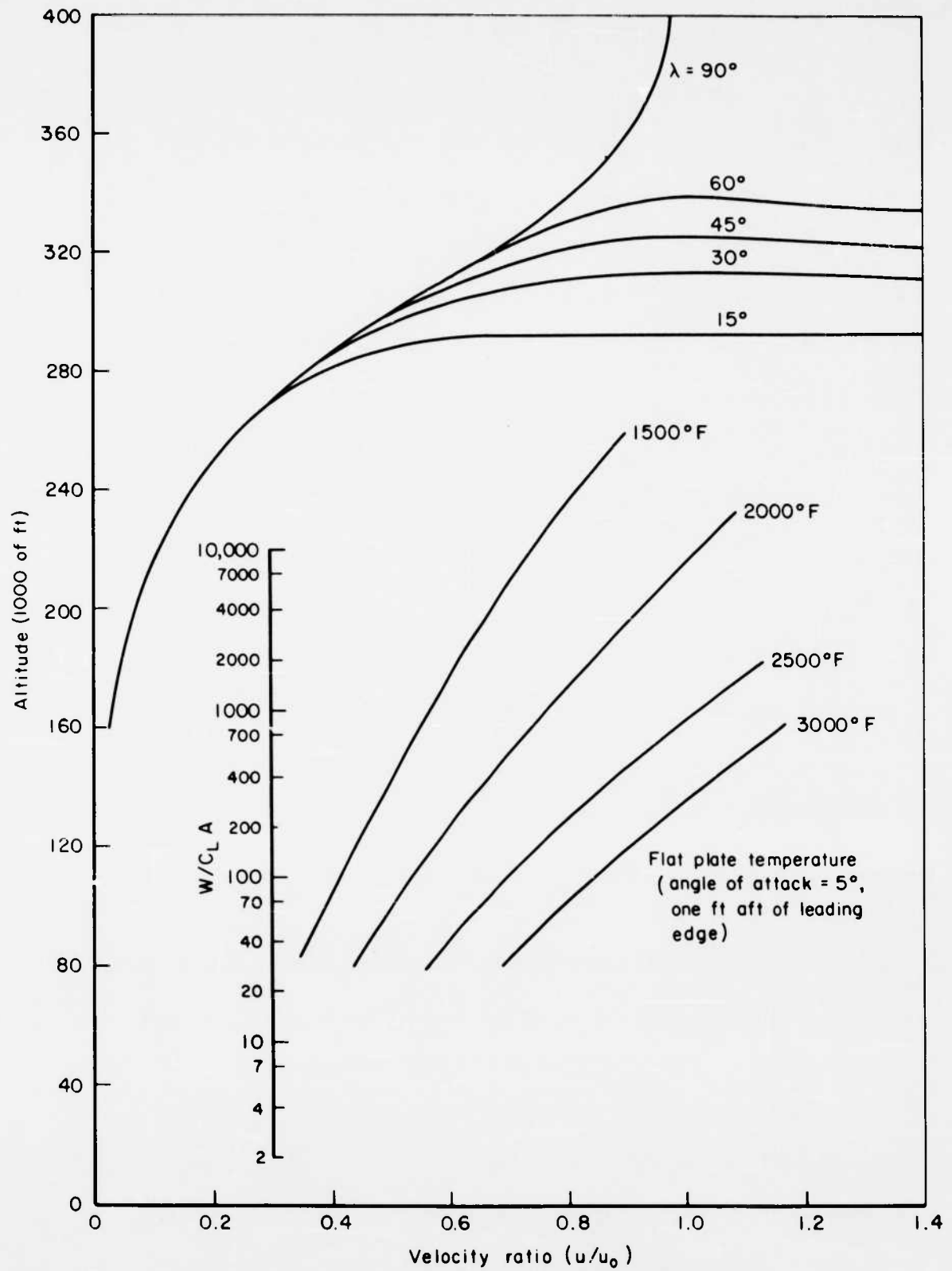


Fig. 16— Glide reentry computer

loading of 1 lb/ft^2 ($W/C_L A$). The logarithmic scale for $W/C_L A$ shows the position of the velocity axis for other values of wing loading. Thus, to construct the altitude-velocity profile for any configuration it is necessary to:

1. Mark velocity and altitude axes on a piece of graph paper to the same scale as shown in Fig. 16.
2. Place the graph paper over Fig. 16.
3. Move the graph paper in a vertical direction, keeping the altitude axes aligned until the velocity axis on the graph paper lies over the design $W/C_L A$.
4. Fasten the graph paper and Fig. 16 firmly together in this position.
5. Trace the desired altitude-velocity profile on the graph paper.
6. To obtain equilibrium temperatures for a flat plate one foot aft of the leading edge at an angle of attack of 5° , unfasten the graph paper from Fig. 16 and align both axes on both pieces of paper. Then trace the temperature contour of interest.

The result of these manipulations is the altitude profile as a function of vehicle velocity.

Another problem that can be solved is the specification of the maximum value of $W/C_L A$ if the thermodynamics of the vehicle materials are known. In this case, the temperature profile of interest is constructed as described in Step 6 above. The graph paper is moved in a vertical direction as before, until the altitude velocity profile just touches the temperature contour on the graph paper. The maximum value of $W/C_L A$ is then found below the velocity axis on the graph paper.

Appendix B

TABULATION OF THE RANGE FUNCTION

This appendix consists of a tabulation of the range function, $F(x)$, referred to in the text of this Memorandum. This function, while not complicated, is somewhat unwieldy from a numerical standpoint, particularly if repeated calculations are made for many different descents into the earth's atmosphere. In this Memorandum, only partial descents into the atmosphere are considered, but the table has been prepared so that velocities down to 2594 ft/sec can be considered, as would be necessary in the investigation of a reentry into the earth's atmosphere. Below this velocity, certain effects neglected in the analysis would become too large to ignore.

The range function allows rapid determination of the distance that a reentry vehicle travels along a particular minor circle path as a function of x , the ratio of the vehicle velocity to earth skimming orbit velocity (25,940 ft/sec).

$$F(x) = 1 - \frac{x^2}{\sin^2 \lambda} - \frac{1}{\sin \lambda} \sqrt{\frac{x^4}{\sin^2 \lambda} - 2x^2 + 1}$$

The parameter λ is merely the radius of the circle on the earth's surface expressed as an earth-centered angle. The special case where $\lambda = 90$ deg is an in-plane descent with no turning. For this descent, the range function degenerates into a simpler function which is not so tedious in hand calculations. Pages 45 to 103 show the range function and the logarithm of the absolute value of the range function in 0.001 increments of x for the minor circle turns defined by $\lambda = 30$ deg, $\lambda = 45$ deg, and

$\lambda = 60$ deg. The value $\lambda = 45$ deg is of particular interest in reentry problems since this minor circle path results in the maximum cross range in an out-of-plane descent.

For those not familiar with digital computer printout routines, entries in the tabular material are shown in a form involving exponential powers of 10. A number, such as 1.012, is written as 0.10120E 01, or as another example, the number 0.001012 would be written as 0.10120E-02. The numbers following the letter E in the group simply indicate the number of places the decimal point should be shifted to the right. If a dash is used following the letter E, the shift of decimal point is to the left.

$\lambda = 30 \text{ deg}$

(19 pages)

X	F(X)	LOG F(X)
1.00000E-01	-0.10203022E 01	0.20098896E-01
0.10100E-00	-0.10207166E 01	0.20504938E-01
0.10200E-00	-0.10211353E 01	0.20915091E-01
0.10300E-00	-0.10215584E 01	0.21329369E-01
0.10400E-00	-0.10219859E 01	0.21747775E-01
0.10500E-00	-0.10224178E 01	0.22170317E-01
0.10600E-00	-0.10228542E 01	0.22596996E-01
0.10700E-00	-0.10232949E 01	0.23027785E-01
0.10800E-00	-0.10237401E 01	0.23462716E-01
0.10900E-00	-0.10241897E 01	0.23901805E-01
0.11000E-00	-0.10246437E 01	0.24345019E-01
0.11100E-00	-0.10251022E 01	0.24792386E-01
0.11200E-00	-0.10255652E 01	0.25243884E-01
0.11300E-00	-0.10260326E 01	0.25699551E-01
0.11400E-00	-0.10265045E 01	0.26159363E-01
0.11500E-00	-0.10269808E 01	0.26623297E-01
0.11600E-00	-0.10274617E 01	0.27091425E-01
0.11700E-00	-0.10279471E 01	0.27563710E-01
0.11800E-00	-0.10284369E 01	0.28040136E-01
0.11900E-00	-0.10289313E 01	0.28520757E-01
0.12000E-00	-0.10294303E 01	0.29005529E-01
0.12100E-00	-0.10299337E 01	0.29494458E-01
0.12200E-00	-0.10304417E 01	0.29987581E-01
0.12300E-00	-0.10309543E 01	0.30484867E-01
0.12400E-00	-0.10314713E 01	0.30986351E-01
0.12500E-00	-0.10319930E 01	0.31491987E-01
0.12600E-00	-0.10325193E 01	0.32001843E-01
0.12700E-00	-0.10330503E 01	0.32515871E-01
0.12800E-00	-0.10335857E 01	0.33034067E-01
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0.13000E-00	-0.10346705E 01	0.34083080E-01
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0.13300E-00	-0.10363325E 01	0.35688099E-01
0.13400E-00	-0.10368958E 01	0.36231527E-01
0.13500E-00	-0.10374638E 01	0.36779160E-01
0.13600E-00	-0.10380365E 01	0.37331001E-01
0.13700E-00	-0.10386139E 01	0.37887067E-01
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0.13900E-00	-0.10397828E 01	0.39011852E-01
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0.14600E-00	-0.10440234E 01	0.43081985E-01
0.14700E-00	-0.10446484E 01	0.43680414E-01
0.14800E-00	-0.10452782E 01	0.44283083E-01
0.14900E-00	-0.10459128E 01	0.44890018E-01
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(19 pages)

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(19 pages)

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